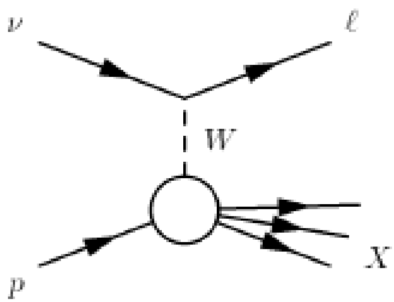
High Energy Physics

Lecture 10

A) Neutrino Deep Inelastic Scattering
B) Symmetries: Parity, Charge Conjugation, Combined Inversion, *CP* violation.

Neutrino Deep Inelastic Scattering



Feynman diagram of neutrino-proton DIS the process shown has a charged outgoing lepton: this is a Charged Current reaction in which a charged IVB ***W*** is exchanged.

The differential cross section is given by

$$\frac{d^2\sigma^{CC}}{dxdy} = \frac{4\pi\alpha^2}{xyQ^2}\eta^{CC}\left\{\left(1-y-\frac{x^2y^2M^2}{Q^2}\right)F_2^{CC} + xy^2F_1^{CC} \pm \left(y-\frac{y^2}{2}\right)xF_3^{CC}\right\}$$

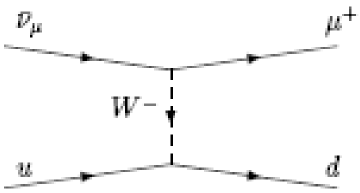
$$\eta^{CC} = \frac{1}{2}\left(\frac{G_F M_W^2}{4\pi\alpha}\cdot\frac{Q^2}{Q^2+M_W^2}\right)^2;$$

$\pm : +(-)$ for incoming $\nu\,(\bar{\nu})$

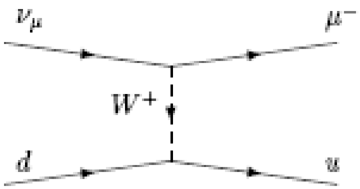
Callan-Gross Relation : $F_2^{CC} = 2xF_1^{CC}$

A deviation from the C-G relation is denoted by $F_L = F_2 - 2xF_1$

<u>Hard sub-process of neutrino-proton DIS:</u>



the dominant sub-process in ***antineutrino-proton*** DIS is the collision of the antineutrino with an up-type quark which turns into a down-type quark; (the down-type antiquark sea is also probed).



the dominant sub-process in ***neutrino-proton*** DIS is the collision of the neutrino with a down-type quark which turns into a up-type quark; (the up-type antiquark sea is also probed).

Within the quark-parton model the corresponding structure functions are:

$$F_2\left(\bar{\nu}\,p \to e^+ X\right) = F_2\left(e^- p \to \nu X\right) = 2x\left(u + \bar{d} + s + c + \ldots\right)$$

$$F_3\left(\bar{\nu}\,p \to e^+ X\right) = F_3\left(e^- p \to \nu X\right) = 2\left(u - \bar{d} - s + c + \ldots\right)$$

$$F_2\left(\nu\,p \to e^- X\right) = F_2\left(e^+ p \to \bar{\nu} X\right) = 2x\left(\bar{u} + d + s + c + \ldots\right)$$

$$F_3\left(\nu\,p \to e^- X\right) = F_3\left(e^+ p \to \bar{\nu} X\right) = 2\left(d - \bar{u} + s - c + \ldots\right)$$

To get the structure functions of **neutrino-neutron** DIS exchange ***u*** with ***d.***

Thus $\boldsymbol{F_2}$ is the total quark+antiquark distribution, and $\boldsymbol{F_3}$ is the valence quark distribution.

The sum and difference of the neutrino and antineutrino differential cross sections, integrated over $\boldsymbol{x}$, have a very simple $\boldsymbol{y}$ dependence:

$$\frac{d\sigma(\nu)}{dy}+\frac{d\sigma(\bar{\nu})}{dy}\propto\left[1+(1-y)^2\right]\int_0^1 x\left[q(x)+\bar{q}(x)\right]dx$$

$$\frac{d\sigma(\nu)}{dy}-\frac{d\sigma(\bar{\nu})}{dy}\propto\left[1-(1-y)^2\right]\int_0^1 x\left[q(x)-\bar{q}(x)\right]dx$$

where $q(x)=u(x)+d(x)+s(x)+\ldots$ and $\bar{q}(x)=\bar{u}(x)+\bar{d}(x)+\bar{s}(x)+\ldots$

Experimental data (from the CDHS experiment) are in agreement with this result: see figure on the next page.
A corollary of this agreement is that $\boldsymbol{F_L}$, *i.e.* the deviation from the Callan-Gross relation, is small.

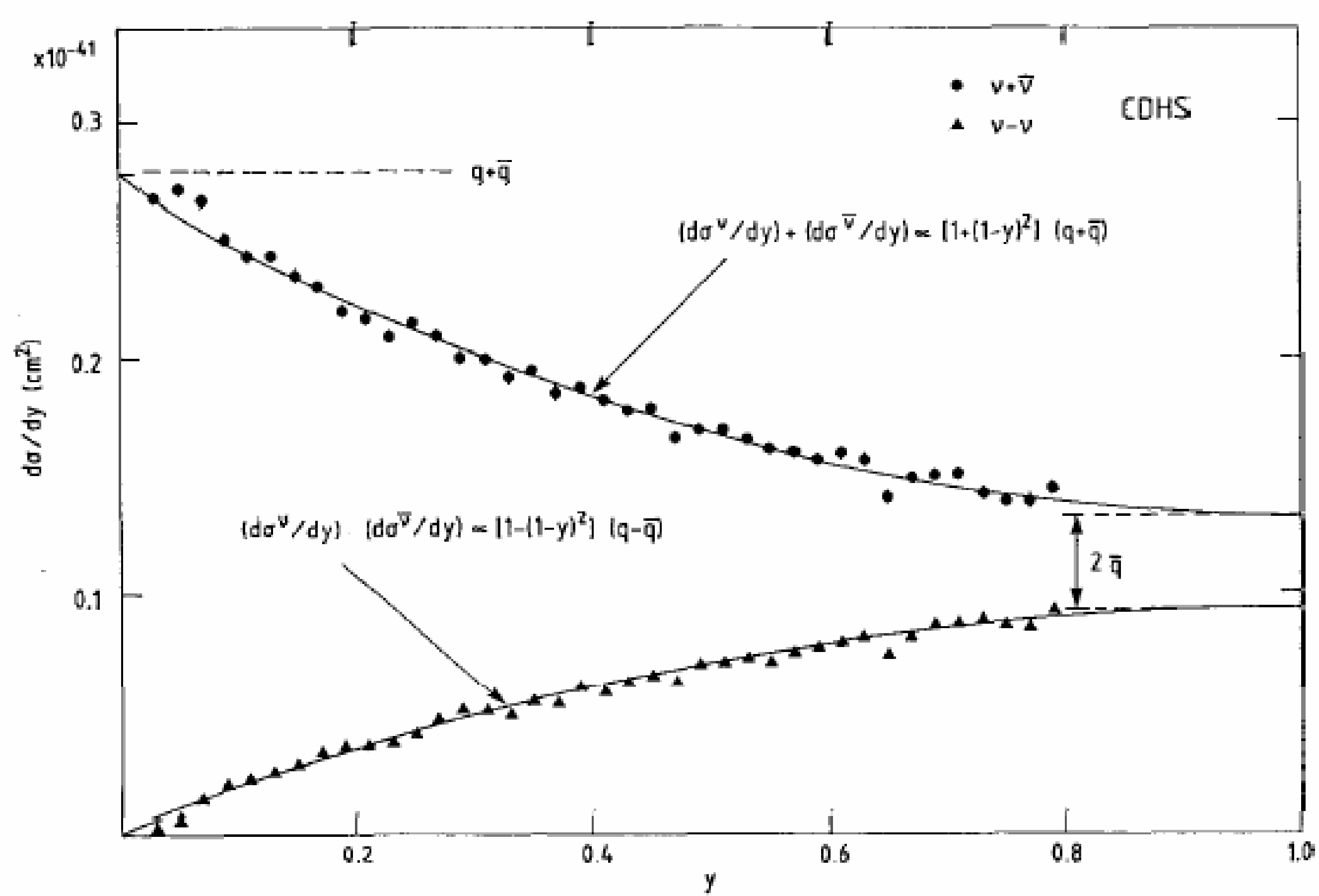


Figure 14 The y-dependence of the sum and the difference of neutrino and antineutrino cross-sections. Spin-$^1/_2$ quarks are expected to have y-dependences $1 + (1\text{-}y)^2$ for the sum and $1 - (1\text{-}y)^2$ for the difference (Ref. 10).

<u>Conclusions</u>: good agreement of theory with experiment means that the process is well understood; it also implies that F_L is small.

Comparison of CC with NC DIS:

The SFs $\boldsymbol{F}_2$ of CC and NC DIS are proportional to the total quark+antiquark distribution. Their ratio is therefore constant:

$$\frac{F_2^{NC}(x)}{F_2^{CC}(x)} = \frac{1}{2}\left[\left(\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2\right] = \frac{5}{18}$$

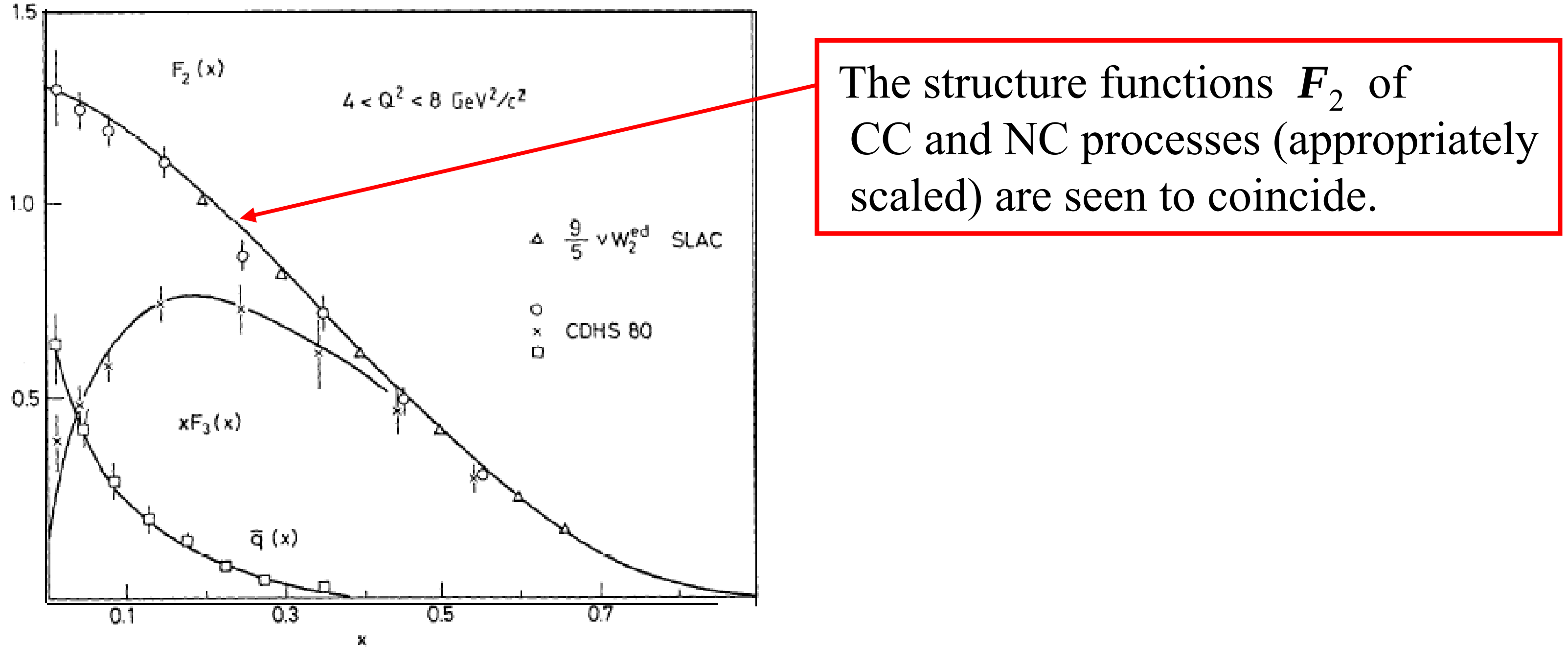
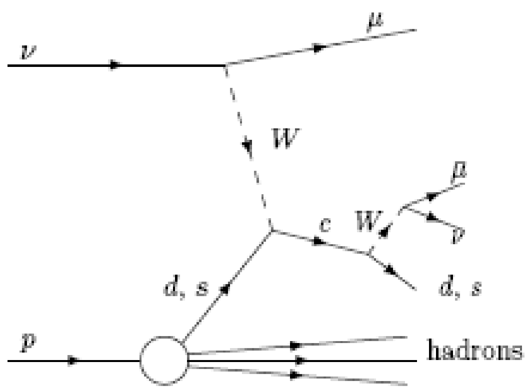


Figure 15 The structure functions $xF_3(x)$, $F_2(x)$, and $\bar{q}(x)$. In the simple quark picture $F_2(x) = x[q(x) + \bar{q}(x)]$ and $xF_3(x) = x[q(x) - \bar{q}(x)]$.

An interesting process initiated by incident neutrinos is opposite-charge muon pair creation:

$$\nu + N \to \mu\bar{\mu}\nu X$$



In the Feynman diagram the particle symbols are understood in a generic sense: if the incident particle is a neutrino (antineutrino), then the outgoing particle is a muon (antimuon) and the exchanged IVB is a W^+ (W^-), the incoming quark is a ***d*** or ***s*** (anti-***d*** or anti-***s***), *etc*.

The main interest of this reaction lies in the following: the cross sections of the hard sub-processes with an incoming ***d*** quark are strongly suppressed:

$$\sigma\left(\nu d \to \mu^- c\right) \propto x d\left(x\right)\sin^2\theta_C; \quad \sigma\left(\bar{\nu}\bar{d} \to \mu^+\bar{c}\right) \propto x d\left(x\right)\sin^2\theta_C$$

$$\sigma\left(\nu s \to \mu^- c\right) \propto x s\left(x\right)\cos^2\theta_C; \quad \sigma\left(\bar{\nu}\bar{s} \to \mu^+\bar{c}\right) \propto x d\left(x\right)\cos^2\theta_C$$

where θ_C is the ***Cabibbo angle***: $\sin\theta_C \approx 0.22$, *i.e.* $\sin^2\theta_C \approx 0.05$; thus in this reaction one probes the strange quark sea!

Experimentally the like-sign muon pair events have a characteristic signature:
(i) opposite-sign muon pairs are seen, like-sign ones are not;
(ii) usually one of the muons has a low energy;
(iii) the low-energy muon is correlated to hadron jet of which the ***c*** quark is a part.

Most recently opposite-sign dimuon events have been studied by the CHARM-II collaboration. Shown here is a schematic view of the CHARM-II detector:

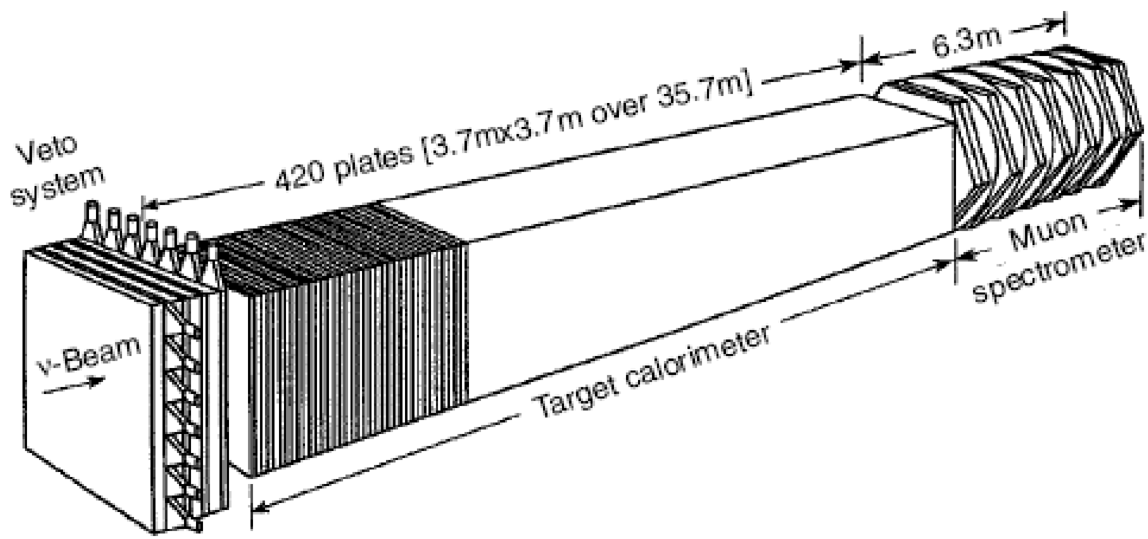


Figure 1: Schematic view of the CHARM II detector.

Example of a like-sign dimuon event seen in the CHARM-II detector: note the much stronger curvature of one of the muon tracks in the magnetic field of the muon chamber, characteristic of a lower momentum.

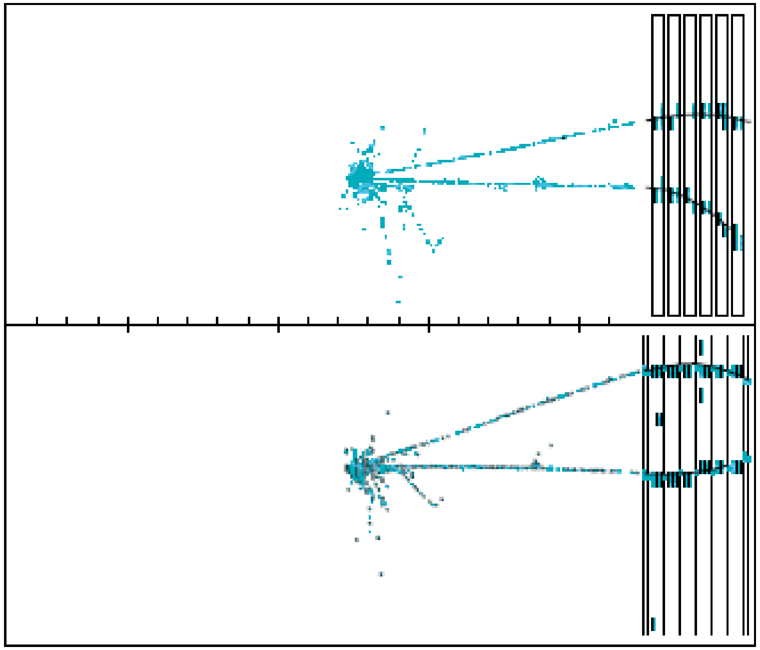


Figure 2: An example of a dimuon event in the CHARM II calorimeter. The two views refer to the horizontal and vertical projections.

Ref.: CERN-EP-98-128 (August 1998)

The result of the CHARM-II study of dimuon events is expressed by the strange sea quark content of the nucleon with respect to the non-strange quark sea:

$$\kappa = \frac{\int_0^1 dx \left\{ xs(x) + x\bar{s}(x) \right\}}{\int_0^1 dx \left\{ x\bar{u}(x) + x\bar{d}(x) \right\}} = 0.39 \pm 0.09$$

Within the experimental errors this result is in agreement with results from experiments CDHS and CCFR:

Experiment	events	κ
CDHS	8600	0.48±0.08
CCFR	4200	0.37±0.05
CHARM-II	3100	0.39±0.09

Summary of discussion of neutrino DIS

Neutrino DIS is complementary to charged lepton DIS in that it probes the nucleon with the ***W*** boson rather than with the photon.

The combined results from CC and NC DIS, together with additional data from hadron-hadron collisions, make it possible to extract results on the parton content of different flavours in the nucleon.

In particular, from neutrino DIS alone one can determine the strange quark content of the nucleon with respect to the non-strange sea quark content.

Symmetries: *Parity, Charge conjugation, CP violation*

- Conservation laws play a special role in Physics: in collisions and in decays we find that the ***charge*** of a system of particles is conserved, also its ***energy***, ***momentum*** and ***angular momentum***.
- Conservation laws are closely related to ***symmetries***: conservation of **energy** to a symmetry in **time**, conservation of **angular momentum** to a **spherical symmetry**.
- In most known processes there is also a ***mirror symmetry***. The corresponding conservation law is called ***parity conservation***. Here I shall discuss the violation of parity conservation in the weak interactions.

Electromagnetic processes are described by ***fields***: an electric field ***E*** and a magnetic field ***B***. They are different at different points in space. Mathematically we say that they are functions of the spatial coordinates *x*, *y* and *z* and of time:

$$\vec{E} = \vec{E}(x, y, z, t); \quad \vec{B} = \vec{B}(x, y, z, t)$$

The equations of electromagnetism are not changed if we replace everywhere (*x,y,z*) by *(-x,-y,-z*). This is equivalent to a ***mirror symmetry***. The corresponding conservation law is called ***parity conservation***.

Particles are also described by fields. This is the essence of quantum theory which is based on the recognition that all particles have wave properties (***particle-wave duality***).

The theories describing particles and their processes are ***field theories***.

Thus for an electron we write a ***wave function***:

$$\psi = \psi\left(x, y, z, t\right)$$

The coordinates do not denote the position of the electron.
The meaning of the wave function is that

$$\left|\psi\left(x,y,z,t\right)\right|^2 dV$$

is the probability to find the electron at time ***t*** in the volume element ***dV*** at the point ***(x,y,z).***

Another name for the wave function of the electron is: ***electron field,*** and one says that the electron is a ***quantum of the electron field.***

Similarly a photon is a quantum of the electromagnetic field, *etc*.

If there are several electrons, then the wave function depends on the coordinates of all particles:

The wave function contains all information about the state of the particle or system of particles at time ***t***. That means that it must be possible to predict the state of the system at a later time, ***t+dt***. This is expressed by the Schrödinger equation:

$$i\hbar\frac{\partial\psi}{\partial t}=\hat{H}\psi$$

where $\hbar$ is Planck's constant ***h*** divided by 2π and $\hat{H}$ is an ***operator*** whose mathematical form cannot be found from any more fundamental theory: it mussed be ***guessed*** and then tested by experiment.

For a single electron in the Coulomb field of an infinitely heavy nucleus the Schrödinger equation is in the nonrelativistic case of the form

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\left(\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}+\frac{\partial^2\psi}{\partial z^2}\right)-\frac{Ze^2}{r}\psi$$

(***m*** is the electron mass, ***e*** is the elementary charge, ***Ze*** is the charge of the nucleus which is assumed to be infinitely heavy and located at the origin).

Thus the $\hat{H}$ operator (***Hamiltonian***) is in this case

$$\hat{H} = -\frac{\hbar^2}{2m}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)-\frac{Ze^2}{r}$$

Note that this Hamiltonian does not change ("***is invariant***") if we change the signs of all coordinates:

$$\hat{H}\left(-x,-y,-z,-\frac{\partial}{\partial x},-\frac{\partial}{\partial y},-\frac{\partial}{\partial z}\right)=\hat{H}\left(x,y,z,\frac{\partial}{\partial x},\frac{\partial}{\partial y},\frac{\partial}{\partial z}\right)$$

The transformation $(x,y,z)\rightarrow(-x,-y,-z)$ is called ***space inversion***.

Thus our theory is invariant under space inversion if the wave function has a symmetry:

$$\psi(-x,-y,-z,t)=\pm\psi(x,y,z,t)$$

i.e. the wave functions are either symmetric (***positive parity***) or antisymmetric (***negative parity***) but do not have mixed parity.

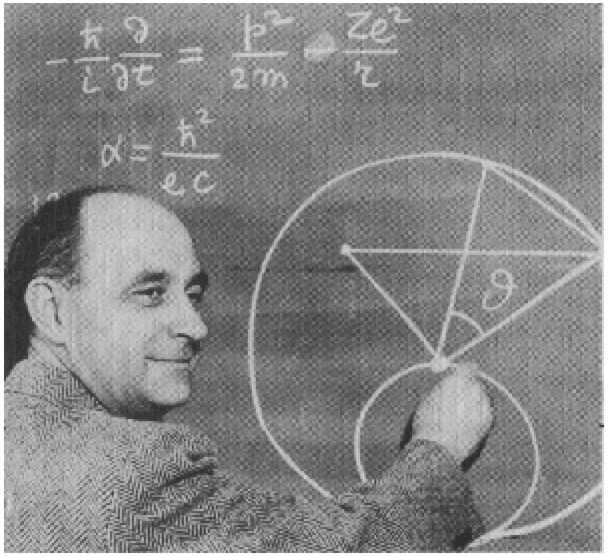
What has been said here for the particular case of the nonrelativistic electron in the Coulomb potential is known to be generally true for the electromagnetic and strong interactions:

Parity is conserved in electromagnetic and strong interactions.

For many years it was believed that parity is also conserved in the weak interactions.

Historical note:

the first theory of weak interactions was formulated in 1934 by **Enrico Fermi** specifically for nuclear beta decays. This theory was modelled after the theory of electromagnetic interactions. It was a parity conserving theory.



E. Fermi, Nobel Prize in Physics 1938.

For a long time the only known weak interaction processes were ***beta decays*** of atomic nuclei.

There were no experimental tests of parity conservation in weak interactions until 1956

Soon after the discovery of the first few elementary particles it was understood that many of their decays were also weak interaction processes. In particular, pion and muon decays are weak processes:

$$\pi^+ \to \mu^+ \nu_\mu; \quad \mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

In order to maintain parity conservation it was necessary to ascribe to each particle its ***parity*** as an ***intrinsic property*** like mass and charge. The parity of a particle can be either positive (+1) or negative (-1).

But intrinsic parity is a relative property: one assigns a positive parity to one particle, for instance to the proton, and then one finds the parities of other particles by analysing processes between these and protons (this is no different from charge!).

Thus it was found that for instance the pion has negative parity relative to the proton, which is conventionally given a positive parity.

The relation between the parities of particles and antiparticles is different for spin ½ particles (fermions) and spin 0 or spin 1 particles (bosons):

An antifermion has the ***opposite*** parity of the fermion
An antiboson has the ***same*** parity as the boson.

Therefore the ***antiproton has negative parity*** since we arbitrarily give the proton a positive parity. (Proton and antiproton are spin ½ fermions.)

Since it was found that the π^- had negative parity, therefore the π^+ also had to have negative parity. (Pions are spin 0 bosons.)

Parity is ***multiplicative*****:** the parity of a system of two particles is the product of their parities and of the parity of their relative motion.

Then it follows rigorously that a two-pion system has positive parity and a three-pion system has negative parity, provided their relative angular momentum is zero.

Then, if we discover a particle that decays into a pair of pions, then we know that it has positive parity, and if it decays into three pions, then it has negative parity.

By 1956 there arose a difficulty, the "***tau-theta paradox***"**:** there were two particles that looked much the same but one of them decayed by weak interaction into two pions and the other into three pions:

$$\tau \to \pi^+ \pi^+ \pi^-; \quad \theta \to \pi^+ \pi^0$$

(this tau not to be confused with today's tau lepton**!**).

At first the experimental data were not very accurate, so the tau and theta could be different. But with improved techniques they looked more and more similar, so it became hard to maintain that they were different particles.
In particular, from their production in strong interaction processes one had to conclude that they both had negative parity.

T.D. Lee and **C.N. Yang** proposed that they were the same particle, and therefore parity had to be violated in weak interactions.
Today this particle is called K^+.

Parity violation in weak interactions was soon demonstrated in several experiments: in nuclear beta decay and in muon decay.

Today parity violation is understood to be a general property of the weak interactions.

For their discovery of parity violation, T.D. Lee (left) and C.N. Yang (right) received the Nobel Prize for Physics in 1957

Actually, it is not quite correct to say that Lee and Yang did discover the violation of parity. What they did was to show that there had been no experiments to test the hypothesis of parity conservation in the weak interactions, and they suggested ways of setting up experiments to carry out such tests.

The citation of their Nobel prize award makes this point quite specifically:

"*for their penetrating investigation of the so-called parity laws which has led to important discoveries regarding the elementary particles*"

Parity violation in processes involving neutrinos can be understood in the following way.

The neutrino is a zero-mass spin ½ particle. Therefore its spin must be pointing on general grounds either along its direction of motion or in the opposite direction, but never at an angle to its direction of motion.

In the former case it is said to be ***right-handed***, and in the latter case it is ***left-handed***.

There are therefore three possibilities:

(i) All neutrinos are right-handed,
(ii) All neutrinos are left-handed;
(iii) Neutrinos can be left-handed and right-handed.

There is no theory that can tell which of these is realised in nature.

The empirical evidence is that all **neutrinos** are **left-handed** and all **antineutrinos** are **right-handed**.

Now if we look at the mirror image of a neutrino, then that is still a neutrino. But a left-handed screw (or a left-handed helix) seen in a mirror is a right-handed screw, and a left-handed neutrino seen in a mirror is a right-handed neutrino. But that does not exist. And that is why parity is violated.

The argument is not so simple when we consider the weak interactions of particles of nonzero mass. Here we take the evidence of parity violation to construct the theory.

But first some jargon. The projection of spin on the momentum vector is called ***helicity***. The helicity of a massive particle can be positive (right-hand screw!) or negative (left-hand screw).

The weak interactions are carried by the intermediate vector bosons. In order to account for the empirically established parity violation one is forced to accept the following result:

The *W* boson couples only to the left-handed components of fermions;
The *Z* boson couples to the left- and right-handed components but with different strength.

Charge Conjugation; combined inversion *CP*

Charge conjugation is the name of the operation that takes a particle to its antiparticle without affecting space and time. If we denote this operation by ***C***, then we have for example

$$\nu_L \xrightarrow{C} \overline{\nu}_L$$

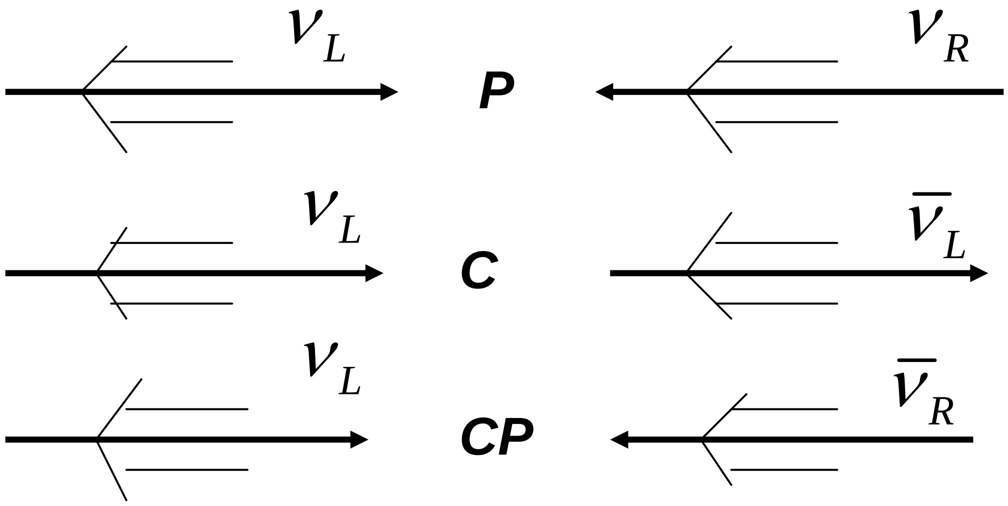
where the subscript ***L*** reminds us of the handedness of the neutrino and antineutrino. But left-handed antineutrinos do not exist. Therefore the charge conjugation symmetry is also violated.

However, if we combine the two operations ***C*** and ***P*** (parity), then we have the following:

$$\nu_L \xrightarrow{C} \overline{\nu}_L \xrightarrow{P} \overline{\nu}_R$$

This is shown in the following figure:

the simple arrows represent the momenta; the broad arrows represent helicity; the parity transformation ***P*** takes the neutrino to an (non existing) right-handed neutrino; charge conjugation ***C*** takes the neutrino to an (non existing) left-handed antineutrino; the combined inversion ***CP*** takes the neutrino to the right-handed antineutrino.



This was essentially the argument of Landau (1957) by which he showed that the combined inversion ***CP*** is a good conservation law.

L.D. Landau

But the argument is not convincing if the weak process does not involve neutrinos. Therefore experimentalists were quick to start checking ***CP*** conservation. The experiment was difficult and the first attempts did not have the necessary sensitivity. But in 1964 a team of four physicist succeeded in showing that the ***CP*** symmetry was broken by a small amount.

The four physicists were J.H. Christenson, J.W. Cronin, V.L. Fitch and R. Turlay. For this discovery Cronin and Fitch received the Nobel Prize of Physics in 1980.

***CP* violation means** that there is in nature an asymmetry between matter and antimatter. In fact, we know that there is this asymmetry because everything we observe in the universe is matter and for all we know there is no antimatter to any significant amount.

A.D. Sakharov

On the other hand, it is a fair assumption that at the Big Bang as much antimatter was created as matter. Then, under complete symmetry, matter should have annihilated with antimatter, leaving a lot of photons but no quarks and leptons (except neutrinos). So the existence of the universe as we know it is evidence of CP violation.

This argument was first put forward by A.D. Sakharov.

The Cabibbo-Kobayashi-Maskawa quark mixing matrix

The key to understanding CP violation is the notion of quark mixing.

This means that the ***mass eigenstates*** of quarks are different from their ***weak eigenstates***.

Denote the up-type quarks by $\boldsymbol{u}_1=\boldsymbol{u}$, $\boldsymbol{u}_2=\boldsymbol{c}$, $\boldsymbol{u}_3=\boldsymbol{t}$, and the mass eigenstates of the down-type quarks by $\boldsymbol{d}_1=\boldsymbol{d}$, $\boldsymbol{d}_2=\boldsymbol{s}$, $\boldsymbol{d}_3=\boldsymbol{b}$. Then the weak eigenstates $\boldsymbol{d'}_i$ of the down-type quarks are related to their mass eigenstates by a unitary transformation:

$$d'_i = \sum_j V_{ij} d_j; \quad with \quad \sum_j V_{ij} V^*_{kj} = \delta_{ik}$$

$\boldsymbol{V}_{ij}$ is the CKM matrix

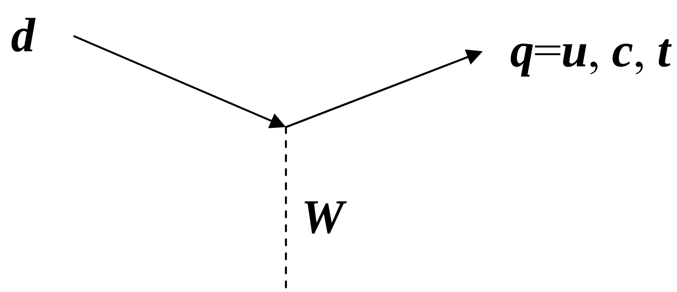
The charge raising weak current is of the following form:

$$J^{\mu +} = \sum \bar{u}_i \gamma^{\mu} d_i' = \bar{u}\gamma^{\mu} V_{ud} d + \bar{u}\gamma^{\mu} V_{us} s + \bar{u}\gamma^{\mu} V_{ub} b + \ldots$$

where the ellipsis stands for terms with ***c*** and ***t*** replacing ***u***.

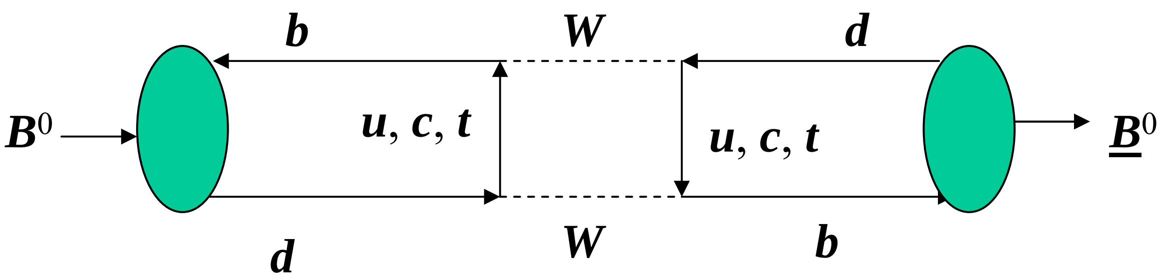
There is a similar expression for the charge lowering current $\boldsymbol{J}^{\mu -}$

Thus there are transition of ***d*** to ***u***, ***c*** and ***t***. The strength of the coupling is determined by the overall coupling constant and by the CKM matrix elements.



$$\propto V_{qd}$$

Then we can construct the following ***box diagram***:



This is a spontaneous transition of a $\boldsymbol{B}^0$ meson into an anti-$\boldsymbol{B}^0$ meson.
The anti-$\boldsymbol{B}^0$ meson can of course make a transition back to a $\boldsymbol{B}^0$ meson.
A sequence of such transitions is called $\boldsymbol{B}^0$- anti-$\boldsymbol{B}^0$ oscillation.

As we see from the diagram, the $\boldsymbol{B}^0$ meson is a ***d***-anti ***b*** bound state and the anti-$\boldsymbol{B}^0$ meson is a ***b***-anti ***d*** bound state:

$$\left|B^0\right\rangle = \left|d\,\bar{b}\right\rangle, \quad \left|\bar{B}^0\right\rangle = \left|\bar{d}\,b\right\rangle$$

We know that the CP operation transforms a particle into its antiparticle.
Thus we have:

$$CP\left|B^0\right\rangle = \left|\bar{B}^0\right\rangle \quad \text{and} \quad CP\left|\bar{B}^0\right\rangle = \left|B^0\right\rangle$$

and we can construct the following CP eigenstates:

$$\left|B_1^0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|B^0\right\rangle + \left|\bar{B}^0\right\rangle\right), \quad \left|B_2^0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|B^0\right\rangle - \left|\bar{B}^0\right\rangle\right)$$

which have CP eigenvalues +1 and -1, respectively.

The evolution of the $\boldsymbol{B^0}$-$\underline{\boldsymbol{B}}^0$ system is governed by the Schrödinger equation

$$i\frac{d}{dt}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix} = H\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}$$

where M and Γ are hermitian matrices. Transitions between $\boldsymbol{B}^0$ and anti-$\boldsymbol{B}^0$ states can take place if $\boldsymbol{H}$ has non-zero off-diagonal elements.

The eigenvectors of H are

$$\left|B_L\right\rangle = p\left|B^0\right\rangle + q\left|\bar{B}^0\right\rangle, \quad \left|B_H\right\rangle = p\left|B^0\right\rangle - q\left|\bar{B}^0\right\rangle$$

where …

$$\frac{q}{p} = \sqrt{\left(M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right) \Big/ \left(M_{12} - \frac{i}{2}\Gamma_{12}\right)}, \quad |p|^2 + |q|^2 = 1$$

If $p = q = 1/\sqrt{2}$, then $\boldsymbol{B}_{\mathrm{H,L}}$ coincide with the $\boldsymbol{CP}$ eigenstates $\boldsymbol{B}_{1,2}$

In this case $\boldsymbol{CP}$ is conserved, otherwise $\boldsymbol{CP}$ is violated.

The eigenvalues of $\boldsymbol{H}$ are

$$\lambda_{\pm} = M - \frac{i}{2}\Gamma \pm \sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right)}$$

where $M{=}M_{11}{=}M_{22}$ and $\Gamma{=}\Gamma_{11}{=}\Gamma_{22}$

(Equality of the diagonal elements of H are a consequence of CPT invariance, where T is time reversal; this is a property of field theory which has a very firm theoretical basis and has been shown experimentally not to be violated.)

The **masses** and **widths** of $\boldsymbol{B}_{\mathrm{H,L}}$ are given by

$$M_{H,L} \equiv \mathrm{Re}\,\lambda_{\pm} = M \pm \frac{1}{2}\Delta M; \quad \Gamma_{H,L} \equiv \mathrm{Im}\,\lambda_{\pm} = \Gamma \pm \frac{1}{2}\Delta\Gamma$$

If at time $t = 0$ we have a $\boldsymbol{B}^0$ meson, then the probability to have a $\boldsymbol{B}^0$ or an anti-$\boldsymbol{B}^0$ at time $t > 0$ is given by

$$P(t) = \frac{1}{4}\left[e^{-\Gamma_H t} + e^{-\Gamma_L t} + 2e^{-\Gamma t}\cos(\Delta M t)\right];$$

$$\bar{P}(t) = \frac{1}{4}\left|\frac{q}{p}\right|^2 \left[e^{-\Gamma_H t} + e^{-\Gamma_L t} - 2e^{-\Gamma t}\cos(\Delta M t)\right].$$

Thus it is seen that the mass difference ΔM between $\boldsymbol{B}_{\mathrm{H}}$ and $\boldsymbol{B}_{\mathrm{L}}$ appears as the oscillation frequency between these states. The experimental value is

$$\Delta M = 0.489 \pm 0.008 \text{ ps}^{-1}$$

Decays of $\boldsymbol{B}^0$ mesons are of two kinds:

(i) decays into states distinct for $\boldsymbol{B}^0$ and anti-$\boldsymbol{B}^0$: these are *CP* conjugate states with equal branching ratios; examples are semileptonic decays:

$$B^0 \to \ell^+ \nu_\ell X^-; \quad \bar{B}^0 \to \ell^- \bar{\nu}_\ell X^+$$

(ii) decays to states, common to $\boldsymbol{B}^0$ and anti-$\boldsymbol{B}^0$; these decays give rise to mixing. An example of this kind is the decay into a $\pi^+\pi^-$ pair:

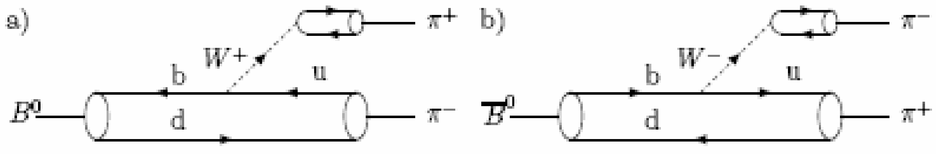


Figure 1: a) $B^0 \to \pi^+\pi^-$ decay , b) $\overline{B}^0 \to \pi^+\pi^-$ decay

As a result of mixing the $\boldsymbol{B}^0$ meson can be an anti-$\boldsymbol{B}^0$ meson at the time of semileptonic decay; we write the reaction equation of this case as a wrong-sign decay:

$$B^0(t) \to \ell^- \overline{\nu}_\ell X^+ \qquad \text{and similarly} \quad \overline{B}^0(t) \to \ell^+ \nu_\ell X^-$$

The decay rate of the wrong-sign decay is proportional to the probability of finding an anti-$\boldsymbol{B}^0$ at time $\boldsymbol{t}$ in the mixed state that at $\boldsymbol{t} = 0$ was a $\boldsymbol{B}^0$; therefore

$$\Gamma\left(B^0(t) \to \ell^- X^+\right) \propto \frac{1}{4}\left|\frac{q}{p}\right|^2 \left[e^{-\Gamma_H t} + e^{-\Gamma_L t} - 2e^{-\Gamma t}\cos\left(\Delta M\, t\right)\right].$$

and similarly for the wrong-sign decay rate of the anti-$\boldsymbol{B}^0$.

Therefore we get an asymmetry defined by

$$A_{s\ell} \equiv \frac{\Gamma\left(\overline{B}^0(t) \to \ell^+ X^-\right) - \Gamma\left(B^0(t) \to \ell^- X^+\right)}{\Gamma\left(\overline{B}^0(t) \to \ell^+ X^-\right) + \Gamma\left(B^0(t) \to \ell^- X^+\right)} = \frac{1-|q/p|^4}{1+|q/p|^4}$$

This is a very small number since $|q/p| \approx 1$

But it illustrates in a simple way the strategy followed in the experimental study of *CP* violation.

Experiments on *CP* violation in ***B*** meson decay were conducted since 1999 at two B meson factories, ***KEKB*** at the KEK laboratory in Japan and ***PEP-II*** at SLAC in California.

Both ***B*** meson factories have asymmetric colliding e^+e^- beams with a centre-of-mass energy equal to the rest energy of the Y(4S) resonance, $E_{c.m.}$ = 10.58 GeV

The Y(4S) resonance decays to 96% into ***B***-anti ***B*** pairs, half neutral and half charged with only about 20 MeV of kinetic energy given to the pair.

The B^0 mesons from Y(4S) decay evolve (oscillate) coherently: if at some instant of time t one of them is a B^0, then the other one is an anti-B^0

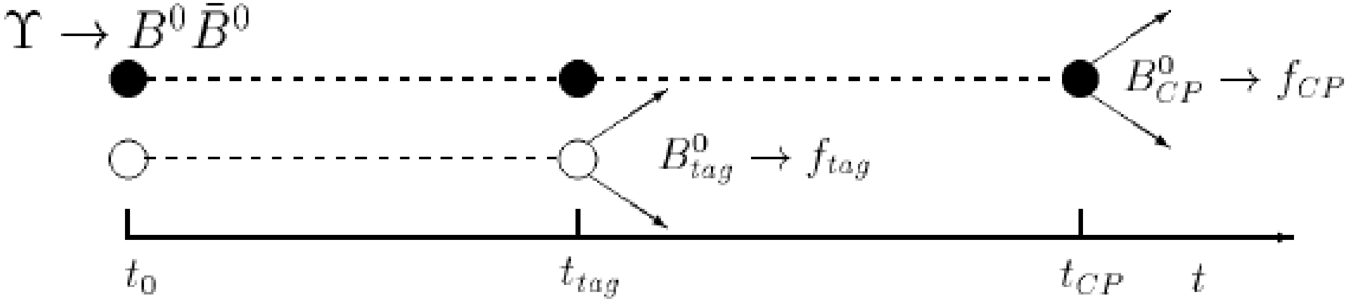


Figure 8: Coherent evolution of the $B\overline{B}$ system from $\Upsilon(4S)$ decay

Suppose one of the mesons decays at time t_{tag} to a flavour specific state f_{tag}. Let its flavour be B^0. Then we know that at that time the other meson is an anti-B^0. Suppose the latter meson decays at time t_{CP} to a state f_{CP} into which both B^0 and anti-B^0 mesons can decay. Then we can find the time dependent asymmetry as defined above:

$$A(\Delta t) \equiv \frac{\Gamma\left(\overline{B}^0(\Delta t) \to f_{CP}\right) - \Gamma\left(B^0(\Delta t) \to f_{CP}\right)}{\Gamma\left(\overline{B}^0(\Delta t) \to f_{CP}\right) + \Gamma\left(B^0(\Delta t) \to f_{CP}\right)}$$

To a very good approximation this can be shown to be theoretically given by

$$\boxed{A(\Delta t) = \operatorname{Im}\lambda \sin(\Delta M\, \Delta t)}$$

with $\lambda = (q/p)\,\bar{A}_{f_{CP}} / A_{f_{CP}}$

here $A_{f_{CP}}$ $(\bar{A}_{f_{CP}})$ is the amplitude of the $\boldsymbol{B}^0$ (anti-$\boldsymbol{B}^0$) decay to $\boldsymbol{f}_{\mathrm{CP}}$

In the absence of CP violation λ is expected to be real and one should see no asymmetry.

Both experiments, Babar and Belle (at SLAC and KEK, respectively) reported non-zero asymmetries in $\boldsymbol{B}^0$ meson decays to J/ψ + K^0

This is shown in the next figure taken from the Babar Web site; similar results were presented by the Belle collaboration.

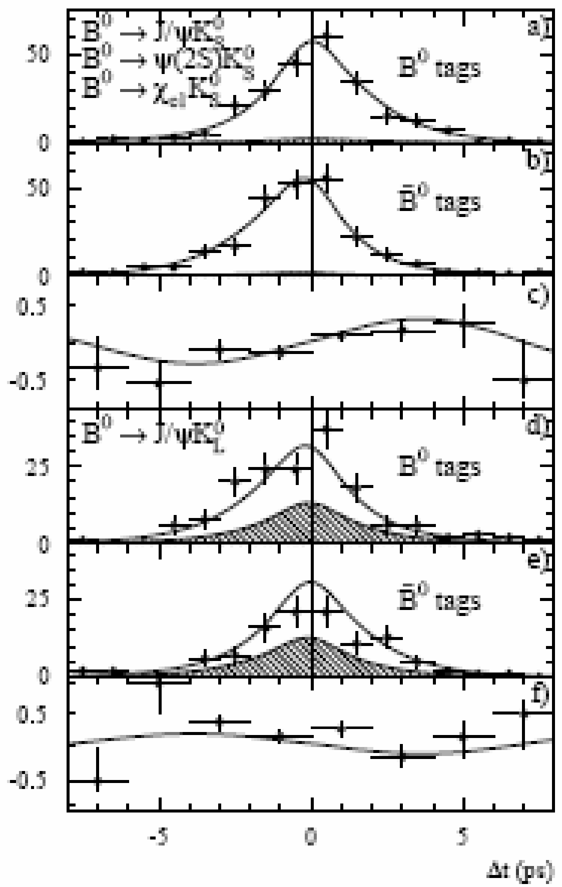


Figure 9: Δt distributions of a) B^0 tagged $B^0 \to (c\bar{c})K_S$ events, b) $\overline{B}^0$ tagged $B^0 \to (c\bar{c})K_S$ events, c) asymmetry; d), e), f) are the corresponding distributions for $B^0 \to (c\bar{c})K_L$ events; the solid curves are fits; the shaded areas are background (from BaBar Web site).